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ABSTRACT

Although pressure forms the basis for understanding topics such as the internal structure of the earth, weather cycles, rock formation, Bernoulli's principle, and plate tectonics, the presence of this concept in the school curriculum is at a minimal level. This paper suggests that the ideas, misconceptions, and perceptions of students have to do with an understanding of the nature of causality. Previous studies have shown that in many examples students have difficulty identifying air pressure as the cause of the results of experiments and demonstrations such as an egg being pushed into a bottle. The results of the study support focusing on causal structure in teaching science concepts. Appended are typical responses of students who moved from simpler models to relational causal models on the open-ended inventory. (Contains 43 references and 10 tables.) (YDS)

Focusing on the Nature of Causality in a Unit on Pressure: How does it Affect Student Understanding?

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This paper is based on the results of research carried out during the second year of the Understandings of Consequence Project. We are continuing to research and develop the ideas presented here. If you have feedback for us or would like to keep in touch with developments on the project, please check our website at http://pzweb.harvard.edu/Research/UnderCon.htm or send us an email at Belinda @ PZ.Harvard.Edu or Tina _Grotzer @PZ.Harvard.Edu.

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Introduction

A rich literature highlights the many learning challenges students face while trying to understand the concept of pressure (e.g. deBerg, 1995; Engel Clough & Driver, 1985; McClelland, 1987; Rollnick & Rutherford, 1993; Shepardson & Moje, 1994). Yet pressure is addressed at a minimal level in most school curriculums. This is surprising considering that pressure forms the basis of deep understanding in transfer topics such as the internal structure of the earth, weather cycles, rock formation, Bernoulli's principle, and plate tectonics. Students cannot conceptualize these topics without an understanding of pressure.

Given the centrality of the concept to so many topics, it behooves us to consider why so many students have difficulty with pressure and why so few teachers feel comfortable teaching it. Why is the concept of pressure so difficult for students to understand? In this paper, we argue that many ideas of students, often termed misconceptions or preconceptions, have at their core an impoverished understanding of the nature of causality. We believe that students make assumptions about the nature of causes and effects and have expectations for how nonobvious, implicit causes and effects in scientific phenomena should behave (Grotzer & Bell, 1999). In particular, these assumptions play out in instances of causation involving pressure and pressure-related topics.

Students explain pressure in a variety of ways (e.g. Camacho & Cazares, 1998; deBerg, 1992; Engel Clough & Driver, 1985; Giese, 1987; Kariotoglou & Psillos, 1993). Based on the extant research, we summarize the difficulties of students into the following categories:

1. *Students reason using obvious variables rather than considering nonobvious variables when determining the causes of pressure-related events.*
2. *Students reason linearly rather than systemically when thinking about pressure.*
3. *Students often think of pressure as a directional quantity, pushing down on things, rather than existing in an omni-directional fashion.*
4. *Students often use the terms pressure and force interchangeably.*

The first two points deal directly with how students reason about the nature of causes and effects. The research study described below focuses on these two areas of difficulty. The other areas were touched upon but not emphasized. We explain the causally focused misconceptions below and draw examples from the literature on pressure to support each.

Students reason using obvious variables rather than considering nonobvious variables when determining the causes of pressure-related events. Our bodies continually adapt to the sea of air in which we live. We are usually unaware of these adaptations, yet they become obvious when pressure changes rapidly, such as when you ascend in an airplane and your ears pop. Often students do not think pressure exists when they cannot easily see an effect. For example, deBerg (1995) found that high school students identified that

the pressure of enclosed air in a syringe increases on compression. This is not startling since they feel the effect of the increased pressure on their hands. The effect is obvious. However, 70% of the students also thought the enclosed air did not have air pressure acting when not in compression. Likewise, Sere (1982) found that 11-13 year-old French children could not imagine pressure without some type of movement associated with it. They considered equilibrium situations to be due to a lack of pressure rather than due to equilibrium between pressing forces.

Kariotoglou and Psillos (1993) also noted that the effects of pressure are often not obvious and undetectable. When students are not aware that pressure is a possible option in their causal reasoning, they may turn to concrete, though incorrect, obvious causes to explain pressure-related situations. For example, when asked why a balloon partially deflates when driving from the mountains to the coast, students reason using obvious agents, such as a hole in the balloon, rather than reasoning using differentials in air pressure between two regions. In a study by Shepardson and Moje (1994), 35% of fifth graders' observations focused on the fire and/or heat in a jar as the cause of a hard-boiled egg being pushed into a bottle rather than considering the less obvious variable of air pressure. Furthermore, post-demonstration/discussion explanations revealed that although 36% of the students mentioned air pressure, 33% of them still stated fire as the cause of the egg entering the bottle. In their causal explanations, students continued to attach salience to what was concrete, which often is disparate with the more abstract reasoning of scientists.

Students reason linearly rather than systemically when thinking about pressure. A simple linear model is unidirectional and involves one to one correspondences between causes and effects (Grotzer, 1993). For example, students focus on a single agent such as the air pressure on the outside of a balloon or a vacuum sucking as causal rather than the cause being the result of a system (of both what is inside and outside the object). Engel Clough and Driver (1985) found that on a syringe task, there was no significant difference between 12, 14, and 16 year-olds in that half (50%) of each age group explained it in terms of pressure actively *sucking* or *pulling*. This linear focus missed broader aspects of the system as a whole. Rollnick and Rutherford (1993) found that elementary school teacher trainees focused on the air pressure on the outside of the cup in explaining why an overturned cup of water remained intact with a piece of cardboard under it. This focus is a form of linear causal reasoning in that the teachers failed to recognize the other agent in the relationship (the air on the inside of the cup) in constructing their causal explanations.

Students' Causal Reasoning in Other Areas of Science

The review above suggests that students' causal reasoning about pressure often does not correspond to that of scientists. This has been documented in other areas such as electricity (e.g. Grotzer & Sudbury, 2000; Shipstone, 1985), ecosystems (e.g. Bell-Basca, Grotzer, Donis, & Shaw, 2000; Green, 1997; Grotzer, 1993, 1989), and force and motion (e.g. Halloun & Hestenes, 1985; White & Frederiksen, 1995). For example, fourth graders often held linear causal models when explaining simple electrical circuits. They reasoned that a bulb lights when electricity flows from the battery to it in a unidirectional,

linear fashion (Shipstone, 1985; Slotta, 1997; Slotta & Chi, 1999). In one study, the students were taught how to think about the differences in the nature of linear versus cyclic sequential and cyclic simultaneous causality (Grotzer & Sudbury, 2000). For instance, they took apart an extension cord as evidence of the circuit as cyclic rather than linear. They role-played how electrons travel in a circuit and contrasted this movement from the perspective of a cyclic sequential model (the electrons travel out of the battery and through the circuit, lighting the bulb) as well as that of a cyclic simultaneous model (the electrons already in the circuit move like a bicycle chain all at once, lighting the bulb attached to the battery). The researchers found that a significant number of students' ideas shifted from linear to cyclic simultaneous models, and that these students did significantly better than control students on an inventory of typically held misconceptions in post-intervention testing.

Bell-Basca et al. (2000) discovered that third graders' conceptions of ecosystems were also linear in nature. Students focused on specific organisms in an uni-directional fashion, such as the fox eating the vole, rather than noting the reciprocity of the relationship or the extended effects of the disappearance of one organism. In the study, students were given the opportunity to consider the differences in the nature of linear versus domino (Grotzer, 1993; Perkins & Grotzer, 2000) and interactive causality. This fostered an awareness of the domino-like effects that the extinction of a species can have on an ecosystem. Students noticed that if the green plants disappeared completely, the effects of their disappearance would extend to organisms beyond those that ate only the green plants. They learned that something can be a cause and an effect at the same time. By understanding this relationship of balance or imbalance between two or more elements, students were able to recognize the reciprocity of organisms -- for instance, voles provide energy for owls and at the same time owls help to maintain the size of the vole population.

The effectiveness of these strategies with third and fourth graders encourages the idea that an intervention designed to address students' difficulties in reasoning about the nature of cause and effect as it pertains to pressure might be similarly effective. We hypothesized that such an intervention might effectively shift eighth graders' linear models of pressure to the more systemic, relational models that scientists employ when considering pressure and pressure-related concepts.

We focused specifically on pressure in this study for several reasons. First, pressure is a generative topic--understanding it enables understanding of many other science concepts. The generativity of pressure in terms of its centrality to the overall curriculum, accessibility for teachers and students, and richness of potential connections (Perkins, 1992) underscore its importance in the curriculum. Secondly, the extant literature clearly highlighted the challenges that students face when trying to understand pressure-related topics. And finally, the underlying causal aspects of pressure seemed make it a good fit for our research.

We explain below the causal components of our intervention. In particular, we suggest that the nonobvious nature of pressure might be a factor in students' lack of awareness of pressure as causal, or if perceived, is often done so in a linear manner rather than relationally.

Nonobvious Causes and Effects

When one considers more complex models to explain scientific phenomena, the nonobvious agents in play require appropriate recognition. One nonobvious variable is air pressure, yet students often fail to note its existence or contribution to an effect. This is not surprising since air pressure itself was not recognized until 1630 when Torricelli discovered that air pressure was the cause for the height to which water could be pumped out of mineshafts (Burke, 1978). This lack of recognition of air pressure persists in students and laypersons today. Tytler (1998) found that students in various age groups (age 6, age 9-10, age 11-12) failed to recognize air pressure while completing science activities focused on air pressure. Students had difficulty shifting their focus from the apparent features of the task to the less obvious agents, such as the air or water involved in the task. Benson, Wittrock, and Baur (1993) found similar results. Students (ranging from second graders to university students) differed from scientists in the perceptions they held of how gases behave. If students have difficulty understanding the nonobviousness of the nature of gases itself, it is hardly surprising that they have trouble understanding gases and their role in air pressure.

Relational Causality

An awareness of nonobvious, hidden causes has the potential to move one towards a relational understanding of phenomena. It enables one to consider a variety of causes and allows for a wider and more systemic perspective. However, even if students notice nonobvious causes, they may still apply a linear causality in their explanation. A simple linear model is unidirectional and involves one to one correspondence between causes and effects (Grotzer, 1993; Grotzer & Bell, 1999). In addition, the linear model inaccurately jumps to a conclusion that fails to engage students in an extended search for causes.

Engel Clough and Driver's (1985) findings imply that students often use linear causal models in reasoning about pressure. They found that half of the 12, 14 and 16 year-olds they surveyed explained drinking from a straw in terms of pressure or a vacuum actively *sucking* or *pulling* rather than a pressure differential between a lower pressure inside the straw and a higher pressure outside the straw as the cause of the event. The linear causal model had salience to students, perhaps because they viewed themselves as taking an active role in drawing the liquid through the straw, rather than the atmosphere pushing the liquid up the straw.

Many phenomena are ill explained by linear models. Typically, as soon as you scratch the surface of a concept and try to explain it at a slightly deeper level, you need to draw upon more complex forms of cause and effect (Perkins & Grotzer, 2000). The linear model is

more often conspicuous, but it does not tell the whole story. Relational causality refers to the patterns of interaction between causes and effects (Perkins & Grotzer, 2000). It is neither A nor B alone, but the interaction of the two that must be considered. For example, when scientists think about pressure, they think about it as a relationship or an interaction--a kind of *two-way* story. They reason relationally in that the air pressure in the balloon is *pushing out* AND the air pressure outside the balloon is *pushing inward* to give a balloon its shape. Thus, areas of higher pressure and lower pressure are compared. The *cause* is a relationship between two or more pressures.

Our goal in the intervention study described below is to help students reason from the relational perspective of scientists. We believe this to be a challenging task because it is much easier to focus on the most obvious single variable as an explanation than to consider multiple variables interacting when reasoning about pressure concepts. Compounded by the fact that we ourselves are immersed in air (and therefore air pressure) but are seldom aware of it, only makes the process more challenging.

We believe that the learning challenge for students is the development of a systemic framework for thinking about pressure that invokes a relational causality for explaining pressure-related phenomena. We expect that this challenges their current conceptions of causality. Students need to think about causality in a way that may contradict their implicit, unexamined assumptions about the nature of causality. An awareness of the nonobvious causes and effects implicit in pressure in conjunction with an understanding of the relational *two-way* nature of pressure may help to move students towards the more complex, scientific reasoning of scientists.

Unfortunately, pressure is typically covered in one or two mathematically focused lessons rather than in a unit that considers its causes and effects by means of a more qualitative approach. deBerg (1992) noted that a focus on quantitative methods without a firm background in qualitative understanding of scientific concepts prevents students from understanding the most fundamental principles of these concepts. The ways in which pressure is addressed in many school curriculums clearly resonates with this. Low levels of causally focused teacher discourse were noted in science lessons with children years 3-6, 7+, and 10+ (Newton & Newton, 2000). Teachers focused more on facts and descriptions than on causes and reasons. Additionally, many teachers are unaware that students already have ideas about pressure that tend to be simple and linear in nature. Teachers may even hold these same simple, linear ideas (Ginns & Watters, 1995; Rollnick & Rutherford, 1990), fostering misconceptions in students and presenting a serious challenge to learning.

Whereas most of the published research around the topic of pressure deals with the identification of students' learning challenges (deBerg, 1995, 1992; Engel Cough & Driver, 1985; Giese, 1987; Kariotoglou & Psillos, 1993), here we report the results of an intervention strategy that addressed these learning challenges by focusing on the nature of causality. If students are just taught information about pressure but not how to structure that information in a causal sense, we expect that they will distort the information to fit a

simplified linear structure. Implementing a similar framework from previous research we have conducted with causality and science understanding (Bell-Basca et al., 2000; Grotzer, 1993, 1989; Grotzer & Sudbury, 2000; Perkins & Grotzer, 2000), we argue that students need to learn both the information and the modes for structuring it. Students are typically unable to construct these relationships on their own. The difficulties that students have with understanding and structuring causality are related to their ability to make sense of the information that they receive. When these difficulties are addressed, students may learn to overcome their misconceptions, develop a broader repertoire of causal models, and more deeply understand pressure-related phenomena.

We attempted to answer three questions in our study: *1. What expectations for causal patterns do students reveal in their initial ideas about pressure?* We hypothesized that students' initial ideas would closely align with the extant literature and include either a lack of pressure as a causal mechanism or an integration of simple, linear causal models to explain pressure-related situations. *2. What is the effect of engaging students in a systemic pressure curriculum that contains causally focused activities designed to reveal the implicit causal structure?* We expected that a qualitatively-based curriculum unit with activities designed to address students' causal difficulties would provide students with opportunities to explore their ideas and compare them to richer, more systemic underlying causal models. *3. What is the impact of explicitly discussing the nature of causal puzzles and their interaction with a more sophisticated scientific understanding of pressure and pressure-related concepts?* We hypothesized that students' assumptions about the nature of causality are so firmly entrenched that explicit discussion addressing their causal presumptions in comparison to scientifically acceptable, relational causal models would be needed to overcome the conceptual challenge of understanding pressure and pressure-related concepts.

Methods

Overview of Research Design:

Two 8th grade classes of the same teacher from the Boston area participated in the study. All students (n = 43) were pre- and post-tested using two inventories. The first was an eleven-question, multiple-choice inventory designed to assess the students' understanding of pressure-related concepts. The second was a four-question, open-ended inventory in which the subjects had to explain, predict, and in all cases justify their explanations of the outcomes of several pressure-related situations. Twelve students from each class (n = 24) were pre- and post-interviewed in depth with the same questions asked in the open-ended inventory. Both classes participated in the pressure unit designed by the research team. In the Systemic Curriculum plus Causal Discussion (SC+CD) group, explicit discussion about nonobvious variables and the nature of linear and relational causality in respect to pressure was added to the unit. The Systemic Curriculum (SC) group had opportunities to extract the underlying causal structures through activities but without the support of explicit discussion.

Procedure:

Misconceptions Inventory: All students (n = 43) were pre- and post-tested using an eleven-question, multiple-choice inventory. The inventory answer choices were designed to resonate with the conceptions students typically hold in the understanding of pressure-related concepts. For each question, four possible responses were given that revealed different misconceptions from the extant research as well as the scientifically accepted explanation. Students chose one response for each question and wrote out an explanation justifying their choice.

Open-ended Inventory: All students (n = 43) were pre-and post-tested using a four-question, open-ended inventory. The questions assessed the obvious and nonobvious causes students cite when explaining pressure-related situations as well as the sophistication of the causal models they employed in their explanations. The first question probed for the causes of a balloon's partial deflation as it was driven from the mountains to the coast. The second question addressed the cause(s) of liquid going into your mouth when you drink from a straw. The third question explored why meteorologists often advise people to partially open the windows in their houses during a hurricane warning. In the final question, students were asked if they thought pressure could change and to give their reasoning for their response.

Interview: Twelve students from each class (n = 24) were pre- and post-interviewed with the same questions that were asked in the open-ended inventory. The purpose of the interview was to gain a fuller picture of the causal models employed by students than was possible with a written inventory. In addition, the format enabled the interviewer to address the linguistic confusion with students' ideas of pressure (Engel Clough & Driver, 1985) undetected by the inventory alone. The interview used a scaffolded approach that began with open-ended questions to offer insight into how students construed the problems and proceeded to more directed probing to assess what they could understand when cued by explicit questions.

Structure of the Unit:

The paucity of developed curriculum units on pressure prompted the research team to design a five-week unit on the topic. The unit addressed specific understanding goals and essential questions related to students' misconceptions within the context of pressure. The unit was based upon discussion, hands-on activities, model design, journal keeping and demonstrations. There were also several points in the unit in which technology was utilized in the forms of video and computer simulations.

The pressure unit developed by the research team addressing the common misconceptions held by students is explained below. Both classes were taught the unit. The additional intervention for the Systemic Curriculum plus Causal Discussion (SC+CD) group involving explicit discussions in focusing systematically and thinking about causality is specified as well.

Curriculum Focus #1: How does pressure affect our daily lives?
Both groups were presented with a series of pressure-related questions such as why new tennis ball cans make a popping sound when opened. Students worked in pairs to write a causal explanation for a subset of the questions. Ideas were shared but little feedback was given as to the accuracy of the responses. These responses were saved and addressed again at the end of the unit.

Curriculum Focus #2: Does pressure exist even when we cannot see the effects easily?
Part A- A balloon was placed in a bell jar, the air pressure inside the jar was lowered, and the students witnessed the balloon expand. Students wrote their causal explanations for the balloon's expansion in size and their ideas were discussed. Those students in the Systemic Curriculum (SC) group discussed how the change in air pressure affected the balloon. Those in the Systemic Curriculum plus Causal Discussion (SC+CD) group discussed why the causes and effects of air pressure are often hard to notice and how they can lead to the inaccurate assignment of cause in pressure-related situations. The SC+CD group then brainstormed and formulated other examples of nonobvious causes in science-related and non-scientific topics.

Part B- Students investigated why a plastic baggie sealed to the rim of a jar could not be pushed into the jar. They also explored why they could not pull a plastic baggie sealed to the rim of a jar out of the jar. Most students were surprised by their inability to push the baggie in or pull the baggie out. Students developed causal explanations to explain these discrepant events and were invited to draw models on the board to support their explanations. The SC group discussed how pressure contributed to the results. The SC+CD group discussed what happened in terms of relational versus linear causality. The nature of the differences between linear and relational causality was explicit in the discussion. Researchers guided students to the realization that a relational causal model more effectively explained their observations than the linear models students placed on the board. Students realized that rather than thinking of pressure in terms of "high" and "low," "higher" and "lower," relational terms, were more appropriate ones to use.

Curriculum Focus #3: What distinguishes force, pressure, and area?
Students did hands-on activities to distinguish pressure, force and area. For example, students determined the amount of pressure they could apply to the floor and how that pressure changed when one stood on two feet versus one foot. They discussed the distinction between force and pressure using the two situations. Students shared ideas with one another in an effort to grasp the distinction between the force and pressure.

Curriculum Focus #4: How is pressure calculated?
Students calculated the amount of air pressure acting on a surface, pressure of their feet on the ground, and water pressure at the bottom of a container. Students in the SC+CD group discussed both the nonobviousness of pressure in these situations as well as how a relational causal model could effectively explain each case.

Curriculum Focus #5: What makes pressure dynamic?
Part A- Students analyzed a dynamic example of pressure differentials by drinking

through a straw. Initially students wrote out their ideas for why the liquid goes up a straw when you drink from it. In the SC group, students shared their ideas and a discussion of pressure differentials ensued with the straw as the focus. In the SC+CD group, the students were presented with three different flask/straw systems and had a contest to see who could drink the liquid from the flask the fastest. The first flask/straw system had a hole in the straw that enabled the lower pressure inside the straw to be equalized with the outside air preventing the formation of a pressure differential. Thus the liquid did not easily rise up the straw when the student tried to drink from it. The second flask/straw system was sealed with a one-holed stopper from which protruded a straw. When the student tried to drink from the flask, he found he could extract a small amount of the liquid but it was immensely difficult to do so. As with the first flask/straw system, stoppering the second flask prevented the formation of a pressure differential when the student tried to drink from the straw. The third flask/straw system contained just the flask, straw and fluid. The student had no difficulty extracting the liquid from the flask due the pressure differential he created when he drank from the straw. Once a winner was determined, students modeled their explanations of what caused the liquid to rise in each of the three flasks. Volunteers placed these on the board. Students discussed the pressure differentials created in each flask/straw system that caused the liquid to rise in the straw until the system reached equilibrium. The relational component of each system was analyzed in detail emphasizing the higher/lower relational causal perspective.

Part B- Students engaged in activities focused on Boyle's Law and Charles Law. In the SC+CD group, students discussed each example explicitly in terms of relational causality.

Curriculum Focus #6: How does pressure relate to weather?
Students discussed the ways in which pressure relates to weather. In the SC group, students tracked how changes in barometric readings are indicative of different weather patterns. In the SC+CD group students discussed how wind is caused by areas of higher pressure flowing towards areas of lower pressure until equilibrium is reached.

Both groups learned a great deal about pressure and pressure-related concepts and had opportunities to extract the underlying causal structures embedded within the activities. However, in the Systemic Curriculum plus Causal Discussion (SC+CD) group, the explicit discussions about causality were a marked attempt to move students towards more sophisticated reasoning of pressure and pressure-related concepts.

Scoring

Open-ended Inventory (OEI):

Causal Model Type

The scoring scheme for the inventory questions was developed and refined. The first three questions were scored in the following ways. First, we assessed the level of causal reasoning students employed using a four-point scale.

Responses were scored zero points if they mentioned a causal mechanism other than pressure. These responses tended to focus on features of the objects or the immediate surroundings such as *"it must get out by a little hole in the rubber."* Dynamic explanations such as *"when the straw is sucked on it directs the liquid up the straw and into your mouth"* were also mentioned.

Responses were scored one point if pressure was mentioned as an entity in itself *acting* in some way with no explicit causal explanation. Examples include, *"pressure acts like a vacuum," "the wind is blowing very hard, it causes force and pressure and that force and pressure could break the windows," or "pressure makes the liquid go up the straw."*

Responses were scored two points if pressure was discussed with the focus on one side of the relationship in a linear, one-way fashion. These might include, *"the air pressure pushes down on the liquid"* or *"pressure pushed against it."*

Responses were scored three points if they implied a relationship but both sides of the relationship were discussed separately or not explicitly. Examples include, *"you are evening out the air pressure between the inside and the outside of your house"* or *"here is low pressure in the straw so the high pressure from the outside pushes on the liquid."*

Responses were scored four points if the relationship was explicit by means of a differential with use of terms such as "higher and lower," "more and less," or "greater and lesser." Responses may also have mentioned the inside and outside pressure trying to equalize or balance out. Examples include, *"The balloon deflated because it was inflated with the air in the mountains, which has less pressure than the air on the coast. So when she got to the coast, the air pressure outside was greater than the air pressure inside the balloon, causing it to deflate" or "When you first suck on the straw, you remove the air out of the straw. This makes the pressure outside of the straw greater than the pressure inside the straw. Now the air needs to be in equilibrium, so to do this, the water goes up the straw until the pressure is equalized."*

Two independent scorers rated the data. One scorer scored 100% of the data; the second scorer scored a subset of 25% to check for interrater reliability. Initial agreement was assessed using a Pearson Product Moment Correlation ($\underline{r}$ = .96) on Question One, ($\underline{r}$ = .97) on Question Two, and ($\underline{r}$ = .97) on Question 3. Differences were discussed until 100% agreement was reached.

Conceptual Change

The data was also assessed to reveal the specific types of conceptual change that students made from pre to post on the OEI. The comparison of the specific changes reflects the sophistication of the students' causal reasoning more effectively than gain scores alone. For example, a student who moved from no model (0 points) to a linear model (2 points) would have a gain score of two points. A student who moved from a linear model (2 points) to a complex relational model (4 points) would also have a gain score of two points. Yet the sophistication of the gains themselves are clearly different. Therefore a

comparison was made between students' pre- and post-test scores and a value assigned to reflect the type of conceptual change that the student attained. The following chart details the breakdown of conceptual change assignments:

- simpler model to a complex relational model = 4
- simpler model to a simple relational model = 3
- simpler model to a linear model = 2
- no model to pressure as 'entity' model = 1
- no model change = 0
- regression to lower model type = -1

Interview:

The questions used for the interview were the same as those used in the OEI. Therefore the interviews were scored for the causal models employed using the same coding format explained as that of the open-ended inventory. In addition, the conceptual changes students made from pre to post were assessed as outlined above.

Two independent scorers rated the data. One scorer scored 100% of the data; the second scorer scored a subset of 25% to check for interrater reliability. Initial agreement was assessed using a Pearson Product Moment Correlation ($\underline{r}$ = .98) on Question One, ($\underline{r}$ = 1.0) on Question Two, and ($\underline{r}$ = .95) on Question 3. Differences were discussed until 100% agreement was reached.

A second pass was done on the interviews to assess students' unscaffolded responses. This was done because the students, during the course of the interview, tended to consider variables that they had not initially. The scoring of the unscaffolded response was intended to capture their initial, unprobed explanation in contrast to their ultimate (probed) model.

Two independent scorers rated the data. One scorer scored 100% of the data; the second scorer scored a subset of 25% to check for reliability. Initial agreement was assessed using a Pearson Product Moment Correlation ($\underline{r}$ = .82) on Question One, ($\underline{r}$ = .99) on Question Two, and ($\underline{r}$ = .97) on Question 3. Differences were discussed until 100% agreement was reached.

Misconceptions Inventory:

Each question on the multiple-choice misconceptions inventory contained one answer that best matched the scientifically accepted explanation. Students' responses were scored for whether or not they matched this explanation. Students were then assigned an overall general score for all inventory questions.

Results

Open-ended Inventory and Interview Data:

The inventory and interview data revealed the type(s) of causal models the students employed regarding the three pressure-related questions. The questions probed students' ideas about: (1) the causes of a balloon's partial deflation as it was driven from the mountains to the coast; (2) the cause(s) of liquid going into your mouth when you drink from a straw; and (3) why meteorologists often advise people to partially open the windows in their houses during a hurricane warning. The data also revealed the specific types of conceptual changes that students made as a result of the study, such as a shift from conceptualizing pressure in terms of a linear model to that of a relational model.

What expectations for causal patterns do students reveal in their initial ideas about pressure?

Students' initial causal models on the open-ended inventory fit those found in the extant research. Of the 129 responses for the three questions asked on the inventory, almost half (49%) of the students' responses made no mention of pressure in their causal reasoning. This finding replicates those of Tytler (1998), Shepardson and Moje (1994) and Benson, Wittrock, and Baur (1993) where students failed to recognize pressure as a nonobvious causal variable. Thirty-three percent (33%) of the responses mentioned pressure in terms of either an entity or a linear model while 19% used pressure in terms of a relational model. Typical responses from students on each question and the causal model type they used include the following:

Jan buys a thank-you balloon for her house sitter while on vacation in the mountains. After driving home to her beach house on the coast the balloon is partially deflated. Why do you think the balloon deflated?

- [Subject #19] -- "...the balloon deflated because it was not completely airtight" = 0 points- causal mechanism other than pressure.
- [Subject #22] -- "...the balloon deflated because the atmosphere's pressure was different up in the mountain than it is down here" = 2 points- linear model (focus on air outside of balloon only)

What causes the liquid to go into your mouth when you drink from a straw?

- [Subject #19] -- "...making a sucking action much like a vacuum" = 0 points- causal mechanism other than pressure.
- [Subject #18] -- "...the pressure and force help it move up through the straw and into your mouth" = 1 point- pressure as an entity.

During a hurricane warning, meteorologists often advise people to partially open the windows in their houses. Why do you think meteorologists tell them to do this?

- [Subject #22] --"...when the windows are open it allows wind to pass through the house rather than knock it over" = 0 points- causal mechanism other than pressure.
- [Subject #1] -- "...the air pressure is different in your house than outside. By opening the windows the air can exchange and the air pressures will be similar" = 3 points- simple relational model.

Likewise it was found that causal mechanisms other than pressure, pressure as an entity, or pressure in terms of a linear model comprised 82% of the 72 responses on the unscaffolded interviews and 64% of the scaffolded interviews.

Students' responses on the misconceptions inventory resonated with the extant literature. For instance, two of the questions on the inventory that focused on linear versus systemic reasoning revealed that 49% of the students reasoned linearly in their choices. In addition, 63% of the students used the terms pressure and force interchangeably in two questions that focused on this misconception.

What is the effect of engaging students in a systemic pressure curriculum that contains causally focused activities designed to reveal the implicit causal structure?

Our study design provided the opportunity for all students, regardless of intervention condition, to learn about pressure by means of a systemic curriculum that included causally focused activities designed to reveal the implicit causal structure. We did not include a traditional control group because an extensive search turned up no comprehensive pressure curriculums that would constitute a reasonable comparison. In addition, prior to the intervention, the teacher in the study spent only a few days on pressure in his normal teaching sequence. We knew from the extant research that students' misconceptions about pressure are typically robust and persist after teaching. So in lieu of comparison to a control group, we looked for pre- to post-test gains and significant conceptual changes in the models that students held at the end of the unit. Although the design limits the interpretation of the results somewhat, it is fairly common in educational research that traditional controls cannot be conducted as in pure experimental conditions (Romberg, 1992). The opportunity to consider outcomes prior to and after treatment offered a valid comparison in view of the information provided by prior research.

Open-ended Inventory (OEI):

Causal Model Type

Students' ultimate causal model types on the open-ended inventory exhibited a more substantial use of pressure as a causal mechanism than was reflected in students' pre-inventory responses. Of the 129 responses for the three questions asked on the inventory, 46% mentioned pressure relationally compared to 19% on the pre-test. Thirty-four percent (34%) of the responses mentioned pressure as either an entity or in a linear model while 20% of the students' responses failed to note pressure in their causal reasoning (see Table 1).

Table 1. Pre and Post Causal Model Types of All Students on the OEI.

Causal Model Type	Pre (N=43)	Post (N=43)
complex relational model	14	39
simple relational model	10	20
linear model	34	37
pressure as 'entity' model	8	7
causal mechanism other than pressure	63	26
	=129 responses	=129 responses

A paired t-test revealed significant differences ($\underline{t} = 6.93$, $\underline{p} < .0001$) between students' pre- and post-totals for causal model type on the open-ended inventory with a mean difference of at least one standard deviation (see Table 2). All students, regardless of intervention condition, benefited from the curriculum. This suggests that a systemic curriculum helped students to understand pressure more deeply than typical instruction as revealed by previous studies (deBerg, 1992; Giese, 1987; Psillos & Kariotoglou, 1999; Shepardson & Moje, 1994; Tytler, 1998).

Table 2. Total Points in Causal Model Types for All Students on OEI.

Open-ended Inventory Analysis- Total Points Means and Std Deviations (N=43)			
Test Category	M	SD	SE of Mean
Pre-total	3.77	2.72	0.42
Post-total	6.91	3.07	0.47
Gain	3.14****	2.97	0.45

***p<.0001.

Achievement Level

A one-way ANOVA was conducted plotting pre-total points for causal model type against achievement level. Achievement level was a significant predictor of students' pre-inventory causal model types ($\underline{F}$ (2, 42) = 7.42, $\underline{p} = .0018$) with the lowest level students doing the least well. This is to be expected given the difficult nature of the topic. Students' post-inventory causal model type gains were also significant ($\underline{F}$ (2, 42) = 23.3, $\underline{p} < .0001$) but total gain scores ($\underline{F}$ (2, 42) = 1.72, $\underline{p} = .19$) were not (see Table 3). This suggests that although the low-level students started at a less sophisticated causal model, their gains were not significantly different from those of students of higher abilities. This is a promising indication that a systemic curriculum can help students of all levels in some way.

Table 3. Causal Model Type Total Points by Achievement Level on the OEI.

Open-ended Inventory Analysis- Achievement Level Means and Std Deviations										
		Pre			Post			Gain		
Achievement Level	N	M	SD	SE of Mean	M	SD	SE of Mean	M	SD	SE of Mean
High	13	5.31**	2.81	0.78	9.31****	1.97	0.55	4.00	3.29	0.91
Medium	21	3.86**	2.44	0.53	7.10****	2.17	0.47	3.24	3.02	0.66
Low	9	1.33**	1.32	0.44	3.00****	2.29	0.76	1.67	1.94	0.65

**p<.01. **** p<.0001.

Interview- Scaffolded and Unscaffolded:

We attempted to address the issue of the linguistic confusion often found in terms of students' ideas (Engel Clough & Driver, 1985) by using the same questions in both the open-ended inventory and the interview. This enabled the research team to acquire a more comprehensive picture of the causal mechanisms employed by students than they might have gotten by using the OEI alone. The scaffolded approach began with open-ended questions and proceeded towards more directed probing by the researchers. However this probing may have caused the students to consider other nonobvious variables, such as pressure. The goal of the interview was to assess students' unexamined (and typically robust) conceptions about pressure-related phenomena and the implicit causal assumptions that these entailed. Therefore we also coded the initial, unscaffolded responses given prior to probing by the researcher.

Causal Model Type

The post interview data reveals similar results to the open-ended inventory. Of the 72 responses for the three questions asked on the unscaffolded interview, 63% employed pressure in a relational model. Twenty-two percent (22%) of the responses mentioned pressure as either an entity or in a linear model, while 15% of the students' responses failed to note pressure in their causal reasoning. On the scaffolded interview, 71% of the responses mentioned pressure in a relational model. Eighteen percent (18%) mentioned pressure as either an entity or in a linear model, while 11% of the students' responses failed to note pressure in their causal reasoning (see Table 4).

Table 4. Pre and Post Causal Model Types of Interviewed Students.

Causal Model Type	Unscaffolded		Scaffolded	
	Pre (N=24)	Post (N=24)	Pre (N=24)	Post (N=24)
complex relational model	11	37	20	45
simple relational model	2	8	6	6
linear model	20	15	13	9
pressure as 'entity' model	3	1	6	4
causal mechanism other than pressure	36	11	27	8
	= 72 responses	= 72 responses	= 72 responses	= 72 responses

Paired t-tests of the difference between students' pre- and post-totals for causal model type revealed significance on both the unscaffolded ($\underline{t}$ = 6.07, $\underline{p}$ < .0001) and scaffolded ($\underline{t}$ = 9.24, $\underline{p}$ < .0001) interview with gains of one and two standard deviations (see Table 5). These findings further support the view that the curriculum was beneficial to all of the students who participated in the interventions.

Table 5. Pre and Post Total Points for Causal Model Types of Interviewed Students.

Interview	Test Category	M	SD	SE of Mean
Unscaffolded (N=24)	Pre-total	3.88	2.40	0.49
	Post-total	8.46	2.65	0.54
	Gain	4.58****	2.43	0.50
Scaffolded (N=24)	Pre-total	5.42	2.99	0.61
	Post-total	9.17	2.50	0.51
	Gain	3.75****	3.03	0.62

***p<.0001.

Misconception Inventory:

A paired t-test of the difference between students' pre- and post-totals for the misconception inventory yielded significant results ($t = 6.81$, $p < .0001$), with a gain of approximately one standard deviation. However, 47% of the students still used the terms force and pressure interchangeably. This misconception was not extensively focused upon in the unit and warrants further study in the future.

These findings suggest that a systemic curriculum helps students to think about pressure in a more scientifically acceptable way. This is very encouraging for several reasons. First, our results suggest that students of all achievement levels gain a more advanced understanding of pressure. In addition, the nature of the gains themselves indicate that a systemic curriculum might help students to overcome some of the challenges inherent in acquiring a deep understanding of pressure as was summarized in the extant research.

The study went a step further in an attempt to ascertain whether explicitly discussing the nature of causality in conjunction with pressure might help students more than the systemic curriculum could alone. We discuss these findings below.

What is the impact of explicitly discussing the nature of causal puzzles and their interaction with a more sophisticated scientific understanding of pressure and pressure-related concepts?

Open-ended Inventory (OEI):

Causal Model Type

The explicit discussion of nonobvious causes and relational causality in the systemic curriculum plus causal discussion (SC+CD) group did not significantly affect the types of causal models students utilized compared to the systemic curriculum (SC) group on the open-ended inventory. A one-way analysis of variance (ANOVA) showed no significant differences between the groups in either post total points (F (1, 42) = 1.68, p = .20) or total gain scores (F (1, 42) = 1.83, p = .18) for causal model type (see Table 6).

Table 6. Means and Standard Deviations for Total Overall Points by Group on the OEI.

Open-ended Inventory Analysis-Causal Model Type Means and Std Deviations										
		Pre			Post			Gain		
Group	N	M	SD	SE of Mean	M	SD	SE of Mean	M	SD	SE of Mean
Systemic Curriculum (SC)	22	3.77	3.16	0.67	6.32	3.17	0.68	2.55	2.76	0.59
Systemic Curriculum plus Causal Discussion (SC+CD)	21	3.76	2.26	0.49	7.52	2.91	0.63	3.76	3.13	0.68

The causal models that students revealed on individual questions revealed similar results. Gain scores on question one (F (1, 42) = 2.35, p = .13), question two (F (1, 42) = .15, p = .70), or question three (F (1, 42) = .48, p = .49) were not significantly different (see Table 7) between intervention conditions.

Table 7. Means and Standard Deviations for Gain Scores on the OEI by Question.

Open-ended Inventory Analysis-Causal Model Type Gain Scores Means and Std Deviations										
		Question One			Question Two			Question Three		
Group	N	M	SD	SE of Mean	M	SD	SE of Mean	M	SD	SE of Mean
Systemic Curriculum (SC)	22	0.68	1.67	0.36	1.05	1.50	0.32	0.82	1.40	0.30
Systemic Curriculum plus Causal Discussion (SC+CD)	21	1.38	1.28	0.28	1.24	1.73	0.38	1.14	1.65	0.36

Conceptual Change

The degree of conceptual change between students who experienced the explicit discussion and those who did not varied considerably. Assessing the data as to the specific types of conceptual change that students made from pre to post revealed significant differences between the groups (F (1, 42) = 5.19, p = .03). This suggests that the sophistication of the causal models differed between the groups. Table 8 reflects the conceptual changes made by students in each group. Students in the systemic curriculum plus causal discussion (SC+CD) group made twice (28 =SC+CD, 14=SC) as many changes from simpler models to relational causal models as did students in the systemic curriculum (SC) group. In particular, thirteen responses of students in the SC+CD group reflected a shift from a linear causal model to a relational causal model compared to two responses in the SC group. This suggests that the explicit discussion of the differences

between linear and relational causality supported students in overcoming their linear models to a greater extent than did participation in causally focused activities without explicit discussion. Typical responses of students who progressed from simpler models to relational causal models can be found in Appendix A.

Table 8. Breakdown of Total Conceptual Changes Made on OEI by Group.

Conceptual Changes	Systemic Curriculum (N=22)	Systemic Curriculum + Causal Discussion (N=21)
simpler model to a complex relational model	10	18
simpler model to a simple relational model	4	10
simpler model to a linear model	9	10
no model to pressure as 'entity' model	5	0
no model change	32	20
regression to lower model type	6	5

Particular questions also yielded significant differences in the measure of conceptual change. Differences were found on question one ($\underline{F}$ (1, 42) = 4.07, $\underline{p}$ = .05), and approaching significance on question three ($\underline{F}$ (1, 42) = 3.60, $\underline{p}$ = .06). No significant differences were found on question two ($\underline{F}$ (1, 42) = .43, $\underline{p}$ = .52). Table 9 shows the means and standard deviations for each question. Table 10 reflects the counts of conceptual changes by each intervention group for each question.

Table 9. Means and Standard Deviations on OEI Detailing Conceptual Change by Question.

Open-ended Inventory Analysis- Conceptual Change Means and Std Deviations										
		Question One			Question Two			Question Three		
Group	N	M	SD	SE of Mean	M	SD	SE of Mean	M	SD	SE of Mean
Systemic Curriculum (SC)	22	1.00*	1.75	0.37	1.18	1.62	0.35	0.95	1.56	0.33
Systemic Curriculum plus Causal Discussion (SC+CD)	21	2.10*	1.81	0.40	1.52	1.81	0.39	1.95	1.88	0.41

*p<.05.

Table 10. Breakdown of Conceptual Changes on OEI by Question.

	Question #1		Question #2		Question #3	
Conceptual Changes	Systemic Curriculum (SC)	Systemic Curriculum + Causal Discussion (SC+CD)	Systemic Curriculum (SC)	Systemic Curriculum + Causal Discussion (SC+CD)	Systemic Curriculum (SC)	Systemic Curriculum + Causal Discussion (SC+CD)
simpler model to a complex relational model	3	8	4	4	3	6
simpler model to a simple relational model	2	2	1	3	1	5
simpler model to a linear model	4	3	2	5	3	2
no model to pressure as 'entity' model	0	0	4	0	1	0
no model change	9	8	10	6	13	6
regression to lower model type	4	0	1	3	1	2

Interview- Scaffolded and Unscaffolded:

Causal Model Type

No significant differences were found between the groups in terms of gain scores in causal model type on the scaffolded ($\underline{F}$ (1, 23) = .28, $\underline{p}$ = .60) or unscaffolded ($\underline{F}$ (1, 23) = .03, $\underline{p}$ = .87) interview.

Conceptual Change

On the measure of conceptual change, total score was approaching significance for the unscaffolded interview ($\underline{F}$ (1, 23) = 3.35, $\underline{p}$ = .08) but not for the scaffolded interview ($\underline{F}$ (1, 23) = .01, $\underline{p}$ = .92). These results suggest that students in the systemic curriculum plus causal discussion (SC+CD) group were more likely to shift to a higher level of causal reasoning in their unscaffolded post-interview responses than those students in the systemic curriculum (SC) group. The lack of significance for the scaffolded interview data supports the notion that probing might have prompted students to consider nonobvious variables (in particular pressure) that they did not consider initially.

Misconception Inventory:

The misconception inventory addressed the misconceptions commonly held by students in the understanding of pressure-related concepts. Each of the eleven-questions was scored for how well it matched the scientifically accepted response. Students were then assigned an overall general score for all inventory questions. A one-way ANOVA showed no significant differences between groups in terms of total gain scores ($\underline{F}$ (1, 43) = .09, $\underline{p}$ = .77) for the inventory.

General Discussion and Conclusions

In this study, students participated in a curriculum designed to illuminate the causal puzzles involved in developing a deep understanding of pressure. The curriculum encompassed activities that focused on and offered insight into the underlying causal structure of pressure-related events. In one of the treatment groups, we contrasted the efficacy of adding explicit discussion of the nature of nonobvious causes and linear versus relational causality to the students' participation in the activities. The results here suggest the importance of providing opportunities, such as the activities here, for students to grapple with their current conceptions of the causal structure embedded in pressure concepts and to develop conceptions that more closely approximate the scientifically accepted models. The results here also provide some limited support for the notion that explicit discussion of the causal puzzles may benefit students.

Students' initial conceptions as revealed by the pre-assessments confirm the findings of the extant research. Our subjects held many of the same misconceptions or preconceptions found previously. For example, students focused on a *vacuum* or *sucking* as the cause of how a liquid rises in a straw when you drink from it rather than with pressure differentials as was shown in Engel Clough and Driver's (1985) findings. In addition, almost half (49%) of our subjects' responses made no mention of pressure. This lack of recognition of pressure as a possible cause was previously documented by Tytler (1998), Shepardson and Moje, (1994) and Benson, Wittrock, and Baur (1993).

Participation in the systemic pressure curriculum with causally focused activities clearly helped students in their understanding of pressure. Despite the typically robust nature of students' beliefs about pressure-related phenomena, we found significant pre- to post-assessment gains in student understanding. It appears that the curriculum focused on causal puzzles helped students understand pressure-related concepts more deeply than the ways in which pressure is usually taught in schools. Comparing the systemic curriculum to a typical pressure curriculum would provide a more conclusive test. That an extensive search failed to turn up a curriculum that offered a reasonable comparison suggests that the pre- to post-assessment is a good alternative for considering the efficacy of the systemic curriculum designed and used in the current study. Romberg (1992) noted that the key to using this strategy lies in gathering sufficient observations prior to treatment so that a trend can be determined and then compared with outcomes after treatment. Our testing methods on the inventories as well as the interview gave us a clear sense of students' initial ideas prior to the intervention and enabled us to detect clear patterns in students' reasoning from which to compare post-intervention results. However, the lack of a substantive unit on pressure to use as a control raises the question of whether the robustness of students' preconceptions is due to persistence despite excellent learning opportunities or the lack thereof. The previous research suggests that in the context of activities that should offer insight into the nature of pressure, students persist in their initial conceptions. Whether this would be the case despite participation in a well-designed pressure unit that does not focus on causal puzzles is an open question. What we can say here with a comfortable level of certainty is that participation in a systemic curriculum unit that does focus on the causal puzzles implicit to pressure-related

phenomena does significantly and substantially advance students' understanding.

In some respects, integrating explicit causal discussion with a systemic curriculum on pressure was beneficial. It led to greater conceptual change for students compared to those students who had only the systemic curriculum. The significant differences between the groups indicate that the explicit causal discussion enabled students in the Systemic Curriculum plus Causal Discussion group to reach a more sophisticated level of conceptual change (i.e. relational model) than students who participated in the systemic curriculum only. However, this conceptual change did not translate into significant differences in gains on the causal model type used on the open-ended inventory or scores on the misconception inventory. It is unclear why this is not the case. Since the ultimate goal of a more sophisticated model is to apply it to pressure-related phenomena to yield increased understanding, the lack of significant differences raises questions. Whether the added causal discussion confers real benefit bears further investigation.

We found it interesting that interviewer probing led many students to consider nonobvious causes that they had not considered in their initial, unscaffolded responses. This sometimes led students to come to relational models that they would not have come to on their own in unscaffolded contexts. This outcome finds support in the existing literature. Green (1997) found that when probing subjects' perceptions of cause and effect relationships in relation to ecosystems, only sixteen percent of twenty-year olds gave two-way causal accounts of a predator-prey relationship when uncued. This number rose to sixty percent in cued conditions. This finding suggests that a possible intervention to be explored involves directing students' attention in various ways to help them detect the causal structures on their own.

Providing students with a causal framework from which to construct meaning can lead to more sophisticated thinking about the concepts under study. However, this does not assure that students will learn scientifically accepted explanations. If students do not also acquire the correct scientific information, they may construct more complex models but with incorrect scientific reasoning. Several students in our study reasoned that there was greater pressure outside than inside a house during a hurricane. Even though they reasoned with a relational causal model, they focused on the intense force of wind that is associated with hurricanes rather than the broader perspective of the hurricane as an area of intense lower pressure compared to the inside of one's home. Students need accurate information and to know how to structure it to emerge with scientifically accepted explanations.

The study results lend support for the more general idea that it is important to provide students with opportunities to develop structural understanding in addition to procedural and conceptual understanding (Grotzer, 2001). Conceptual understanding is often the first order of business in many classrooms and the focus of the curriculum. Procedural knowledge is also taught, such as how to operationalize a question, how to isolate and control variables, and so forth. Structural understanding refers to the way that experts in a domain deal with foundational concepts that impact how experience or information is structured, for instance, the way that one thinks about categorization, causality, or the

nature of numerosity. Commonly, teachers offer students information with little assistance on how to structure that information. Consequently, students may distort the information to fit simplified, default structures that are already a part of their repertoire. This suggests that one cannot teach deep conceptual understanding without attending to structural understanding.

However, it is not common for teachers to focus on causal structure. Newton and Newton (2000) found that half of the teachers they surveyed spent less than 5% of their teaching time using causal questioning. Indeed, it is not even typical for teachers to focus on conceptual models. The topic of pressure is often taught to students with a quantitative, superficial approach (deBerg, 1992). This mathematical focus often supersedes efforts at building the qualitative understanding needed to deeply learn the topic at hand. Researchers have called for conceptual models to support students' quantitative understanding (e.g. Clement, 1982; Clement, Brown, & Zietsman, 1989; Larkin & Chabay, 1989) and for consideration of the relationship between quantitative and qualitative models. For instance, White and Frederiksen (1990; 1995; White, 1993) have called for intermediate causal models and have sought to expose students to models that are causally consistent in the causal agents operating in both the quantitative and qualitative models.

The need to consider structural aspects of how students understand causality and bring this to bear on their science learning has clear support in the literature. For instance, diSessa (1993) examined the role that phenomenological primitives (or p-prims), small knowledge structures that people use to describe a system's behavior, play in students' explanations of science phenomena. These structures compete with scientific notions that involve different causal patterns. Brown (1995) has written about "core causal intuitions" for how people attribute agency and how they assess responses to agency that can lead students astray as they attempt to understand difficult science concepts. Andersson (1986) considered how the primitive notion, learned in infancy, that the nearer the greater the effect, contributed to difficulties in learning a variety of science concepts. Resnick (1994) has investigated how people's assumptions of centralized, deterministic causal agents make it difficult for them to comprehend emergent processes. Chi (2000) suggests that students' difficulties stem in part from differences in the behavior that fits the surface or aggregate level of a phenomenon and those that characterize the micro level. She has argued that effects emerge at the micro level that contradict the surface level. Wilensky and Resnick (1999) similarly have argued that people have difficulty reasoning at the right level when considering complex phenomena. By mixing levels and attempting to apply deterministic, linear cause and effect, people miss the complex emergent effects that can occur when fairly straightforward, linear effects interact. A strong case is made for focusing on causal structure in the context of science learning.

The results reported here lend further support for the case of focusing on causal structure in the context of learning science concepts. The significant increases in understanding following participation in causally focused activities despite the challenges posed by the topic of pressure are promising. Such a focus presents a new lens for considering and developing curriculum that engenders deep understanding.

References

Andersson, B. (1986). The experiential gestalt of causation: A common core to pupils' preconceptions in science. *European Journal of Science Education, 8*(2), 155-171.

Bell-Basca, B., Grotzer, T.A., Donis, K., & Shaw, S. (2000, April-May). *Using domino and relational causality to analyze ecosystems: realizing that what goes around comes around.* Paper presented at the annual meeting of the National Association of Research in Science Teaching, New Orleans, LA.

Benson, D.L., Wittrock, M.C. & Baur, M.E. (1993). Students' perceptions of the nature of gases. *Journal of Research in Science Teaching. 30*(6), 587-597.

Brown, D. E. (1995, April). *Concrete focusing and re-focusing: A cross-domain perspective on conceptual change in mechanics and electricity*. Paper presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

Burke, J. (1978). *Connections*. Boston: Little, Brown & Company.

Camacho, F.F. & Cazares, L.G. (1998). Partial possible models: An approach to interpret students physical representation. *Science Education. 82*(1), 15-29.

Chi, M. (2001, April). *Misunderstanding Emergent Processes as Causal.* Paper presented at the annual meeting of the American Educational Research Association, Seattle, WA.

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics. 50*, 66-71.

Clement, J., Brown, D.E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding "anchoring conceptions" for grounding instruction on students' intuitions. *International Journal of Science Education, 11*, 554-565.

deBerg, K.C. (1992). Students thinking in relation to pressure-volume changes of a fixed amount of air: The semi-quantitative context. *International Journal of Science Education*. 14(3), 295-303.

deBerg, K.C. (1995). Student understanding of the volume, mass, and pressure of air within a sealed syringe in different states of compression. *Journal of Research in Science Teaching. 32*(8), 871-884.

diSessa, A.A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2 & 3), 105-226.

Engel Clough, E. & Driver, R. (1985). What do children understand about pressure in fluids. *Research in Science & Technological Education. 3*(2), 133-144.

Giese, P.A. (1987, July). *Misconceptions about water pressure.* Proceedings of the Second International Seminar: Misconceptions and Educational Strategies in Science and Mathematics, vol. II. Cornell University, Ithaca, NY.

Ginns, I.S. & Watters, J.J. (1995). An analysis of scientific understandings of preservice elementary teacher education students. *Journal of Research in Science Teaching. 32*(2), 205-222.

Green, D.W. (1997). Explaining and envisaging an ecological phenomenon. *British Journal of Psychology. 88*, 199-217.

Grotzer, T.A. (1989). *Can children learn to understand complex causal relationships? A pilot study.* Unpublished qualifying paper, Harvard University, Cambridge, MA.

Grotzer, T.A. (1993). *Children's understanding of complex causal relationships in natural systems.* Unpublished doctoral dissertation, Harvard University, Cambridge, MA.

Grotzer, T.A. (2001). *The Missing Leg: Why Science Classrooms Need to Teach Structural Knowledge in Addition to Conceptual and Procedural Knowledge*. Manuscript in preparation.

Grotzer, T.A. & Bell, B. (1999). Negotiating the funnel: Guiding students toward understanding elusive generative concepts. In L Hetland & S. Veenema (Eds.) *The Project Zero Classroom: Views on Understanding*. Fellows and Trustees of Harvard College.

Grotzer, T.A & Sudbury, M. (2000, April-May). *Moving beyond underlying linear causal models of electrical circuits.* Paper presented at the annual meeting of the National Association of Research in Science Teaching, New Orleans, LA.

Halloun, I. & Hestenes, D. (1985). Common sense concepts about motion. *American Journal of Physics. 53*(11), 1056-1065.

Kariotoglou, P. & Psillos, D. (1993). Pupils pressure models and their implication for instruction. *Research in Science & Technological Education. 11*(1), 95-108.

Larkin, J.H., & Chabay, R.W. (1989). Research on teaching scientific thinking: Implications for computer-based instruction. In L.B. Resnick & L.E. Klopfer (Eds.), *Toward the thinking curriculum.* ASCD.

McClelland, J. (1987). Pressure points. *Physics Education. 22*, 107-109.

Newton, D.P. & Newton, L.D. (2000). Do teachers support causal understanding through their discourse when teaching primary science? *British Educational Research Journal. 26*(5), 599-613.

Perkins, D. (1992). *Smart Schools: Better thinking and learning for every child.* New York: The Free Press.

Perkins, D.N. & Grotzer, T.A. (2000, April). *Models and moves: Focusing on dimensions of complex causality to achieve deeper scientific understanding*. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.

Psillos, D. & Kariotoglou, P. (1999). Teaching fluids: intended knowledge and students' actual conceptual evolution. *International Journal of Science Education. 21*(1), 17-38.

Resnick, M. (1994). *Turtles, Termites, and Traffic Jams: Explorations in Massively Parallel Microworlds*. Cambridge, MA: MIT Press.

Rollnick, M. & Rutherford, M. (1990). African primary school teachers—what do they hold on air and air pressure? *International Journal of Science Education. 12*(1), 101-113.

Rollnick, M. & Rutherford, M. (1993). The use of a conceptual change model and mixed language strategy for remediating misconceptions on air pressure. *International Journal of Science Education. 15*(4), 363-381.

Romberg, T.A. (1992). Perspective on scholarship and research methods. In D.A. Grouws (Ed.), *Handbook of Research on Mathematics Teaching and Learning* (pp. 49-64). New York: Macmillan Publishing Company.

Sere, M. (1982). A study of some frameworks used by pupils aged 11-13 years in the interpretation of air pressure. *European Journal of Science Education. 4*(3), 299-309.

Shepardson, D. & Moje, E. (1994). The impact of a science demonstration on children's understandings of air pressure. *Journal of Research in Science Teaching. 31*(3), 243-258.

Shipstone, D. (1985). Electricity in simple circuits. In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science* (pp. 33-51). Philadelphia: Open University Press.

Slotta, J. D. (1997). *Understanding constraint-based processes: A precursor to conceptual change in physics*. Unpublished doctoral dissertation, University of Pittsburgh, Pittsburgh, PA.

Slotta, J. D. & Chi, M. T. (1999). *How physics novices can overcome robust misconceptions through ontology training*. Manuscript submitted for publication.

Tytler, R.T. (1998). Children's conceptions of air pressure: exploring the nature of conceptual change. *International Journal of Science Education. 20*(8), 929-958.

White, B. (1993). Intermediate causal models: A missing link for successful science education. *Cognition and Instruction*, *10*(1), 1-100.

White, B. & Frederiksen, J. (1990). Causal model progression as a foundation for intelligent learning environments. *Artificial Intelligence, 24*, 99-157.

White, B., & Frederiksen, J. (1995). *An overview of the thinker tools inquiry project*. (Causal Models Research Group Report No. CM-95-04). Berkeley, CA: School of Education, University of California at Berkeley.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology, 8*(1), 3-19.

Appendix A:

Typical responses of students who moved from simpler models to relational causal models on the open-ended inventory included the following:

Students who moved from feature/dynamic model to relational causal model

[Subject #7-pre] -- "The force of your inhaling causes the liquid to go through the straw. Your air is concentrated through that little tube giving it enough force to draw it in."

[Subject #7-post] -- "When you first suck on the straw, you remove the air out of the straw. This makes the pressure outside the straw greater than the pressure inside the straw. Now the air needs to be in equilibrium, so to do this, the water goes up the straw until the pressure is equalized."

[Subject #19-pre] -- "I think the balloon deflated because it was not completely airtight. If the balloon was tied by hand there is a chance a small opening is available for air to travel through."

[Subject #19-post] -- "The balloon deflated because there is less air pressure in the mountains and more on ground closer to sea level. In the mountains the air inside the balloon provided enough pressure to keep the balloon big but sea level air has more pressure and caused the balloon to partially deflate."

[Subject #16-pre] -- "I think they warn people to partially open the windows so the temperature in both areas will stay the same and not rise in the room, or fall too quickly."

[Subject #16-post] -- "Because while the storm is occurring the rain brings low pressure. Inside your house...is a higher pressure. Since the two pressure are different, they will want to create an equilibrium between themselves so they will try to push in or out to reach equilibrium. During this procedure the windows can shatter as the pressure try to equalize themselves."

Students who moved from pressure as feature to relational causal model

[Subject #18-pre] -- "I think that when you are drinking from a straw, then you suck the drink up. The pressure and force help it move up through the straw and into your mouth. The force pushes it up."

[Subject #18-post] -- "Liquid goes into your from a straw because when you suck the air out of the straw there is no pressure pushing down on it. So, the air pressure from outside the glass is still pushing down on the liquid, so the liquid has no place to go, but up the straw."

[Subject #3-pre] -- "I think when there is a hurricane there is so much pressure that it would cause the windows to break if they were closed."

[Subject #3-post] -- "There is high pressure inside and low pressure outside which makes the window break. So it needs to have equilibrium so the window won't shatter during the hurricane."

Students who moved from linear to relational causal model

[Subject #1-pre] -- "When Jan was driving down the pressure in the air wasn't as strong so the balloon started to shrink."

[Subject #1-post] -- "I think this happens because of the pressure differentials. When you buy a balloon in the mountains, the air pressure is less than at sea level. The pressure in the balloon stays the same. The pressure is greater at sea level so it pushes harder on the balloon. The high pressure goes towards the low pressure. That's what makes the balloon deflate."

[Subject #33-pre] -- "I think they tell that to people because the pressure will get so high on the house the windows might break...it could do with the pressure from the winds and when you open the window up the pressure is less so it doesn't break the windows."

[Subject #33-post] -- "Because the pressure inside the house is higher than outside so they try to reach equilibrium. If it does it with the windows shut it will break the glass, so you should leave the windows open a bit."

Students who moved from implicit to explicit relational causal model

[Subject #35-pre] -- "So that if the air pressure changes inside and out the glass won't shatter."
[Subject #35-post] -- "Because the severe change in pressure when the hurricane passes makes the pressure outside less than inside and the windows will blow outward and break so that it can equalize."

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